RESEARCH DEPARTMENT

A method for measuring the vertical radiation patterns of u.h.f. transmitting aerials

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A METHOD FOR MEASURING THE VERTICAL RADIATION PATTERNS OF U.H.F. TRANSMITTING AERIALS

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(1964/79)

D. Maurice

D.J. Neale, Ph.D., B.Sc., Grad. Inst.P.

(R.D.A. Maurice)

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Section Title Page

SUMMARY 1

1. INTRODUCTION 1

2. METHOD OF MEASUREMENT 2

   2.1. Principle of Method 2
   2.2. Instrumentation 3

3. EXPERIMENTAL VERIFICATION OF ACCURACY 5

4. CONCLUSIONS 8

5. REFERENCES 8

6. APPENDIX: COMPUTER PROGRAMMES FOR V.R.P. CALCULATIONS 9

   6.1. Organization of Probe Measurements 9
   6.2. Ancillary Data Required for Programme 10
   6.3. Determination of Element Currents 10

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A METHOD FOR MEASURING THE VERTICAL RADIATION PATTERNS OF U.H.F. TRANSMITTING AERIALS

SUMMARY

The basic methods for determining the vertical radiation pattern (v.r.p.) of an aerial are outlined and compared with a new method which is more convenient for large aerials. Results obtained for a ten-tier aerial by this method and by the usual method of rotating the aerial on a turntable are compared. The procedure for determining the v.r.p.s of larger aerials by the new method, with the aid of two specially developed computer programmes, is outlined.

1. INTRODUCTION

Compared with transmitting aerials for the lower frequency bands, ultra-high frequency (u.h.f.) transmitting aerials employ a greater radiating length measured in wavelengths. By this means they achieve higher gains and hence meet the requirements for greater effective radiated powers (e.r.p.s) with practicable transmitter powers. As a consequence of the increased vertical directivity special measures have to be taken to avoid the occurrence of deep minima in the v.r.p.s, since these result in areas of low field strength. In addition, the main lobe of the v.r.p. has to be tilted downwards towards the horizon in order to secure as large a field strength as possible at the longer ranges.

Measurement of the v.r.p.s of u.h.f. aerials therefore forms an essential part of their acceptance tests. The conventional method of mounting the aerial on its side on a turntable and measuring the pick-up on a distant receiving aerial is, however, impracticable. There are two main reasons for this. First, a multi-tier aerial is of considerable length even at u.h.f. and laying it on its side imposes mechanical difficulties. Second, assuming that the aerial is so mounted, the distance between the turntable and the receiving aerial would have to be prohibitively large for the true far-field v.r.p. to be recorded. For example, the usual criterion is that the path difference between rays travelling to the receiving aerial from the central and outer elements of the array should not exceed $\lambda/16$ for the direction normal to the array,[1] where λ is the wavelength; this means that the measuring distance for a 40λ aerial would have to be 3200λ (approximately 2 km at 500 Mc/s) and an even greater spacing would be required for accurate measurement of the sidelobe structure.[2] In order to avoid errors due to reflexions, this method of measurement could only be carried out in a large open space such as a disused airfield, or between two hill tops.

The possibility of measuring the currents in the radiating elements and computing the v.r.p. was therefore examined in some detail.

For a small array an established method of determining element currents is the 'perturbation method'[3] in which a small series impedance is introduced at each element in turn and the resultant change in input impedance is measured. The accuracy of the perturbation method falls rapidly as the number of elements increases and is considered impracticable for more than ten tiers. Moreover, the construction of u.h.f. radiating elements is often such that perturbations cannot conveniently be made. The perturbation method also suffers from the disadvantage that the phases of the measured currents have an ambiguity of 180° because of a square-root operation in the mathematics. This doubt can always be resolved by inspection with v.h.f. aerials, but difficulties arise with u.h.f. aerials because of the complicated phasing between individual tiers.

In the alternative method[3] which is used at v.h.f., small current measuring probes are clamped to the radiating elements and the outputs of the probes compared. This method cannot conveniently be used at u.h.f. unless the probes are permanently incorporated in the elements. Each element would then require a probe cable in addition to its normal feed cable and the lengths of the probe cables themselves would have to meet very close tolerances. Since this would considerably increase the complexity and cost of an aerial it was considered to be impracticable.

A modification of the probe method was therefore evolved. In this method probes were used to measure the magnetic field near each element in turn and the resulting set of output voltages compared. The ratios of these voltages do not give the exact ratios of the element currents because the voltage induced in each probe depends to some extent on the currents flowing in elements adjacent to the one nearest to the probe. However, sufficient information may be obtained in this way to enable a set of simultaneous equations containing the element currents to be written down and subsequently solved. This method is described in greater detail in the following section.

The computation of a v.r.p. of a multi-element array from the measured currents in each element involves the evaluation of each element's contribution to the far field. In this report it is assumed that all the elements are identical. The case of non-identical elements could, however, be dealt with but would involve a separate calibration experiment for each type of element and the knowledge of the v.r.p. of each type of element.

The accuracy of the method was initially investigated by applying it to a simple array whose radiation pattern could also be measured by rotation on a turntable. The method was then adapted to the measurement of the v.r.p. of the u.h.f. skew aerial at Crystal Palace, and further comparison tests were carried out on a section of this aerial.

2. METHOD OF MEASUREMENT

2.1. Principle of Method

In the method described in this report a small probe is placed close to each of the radiating elements of a u.h.f. aerial in turn and the output voltages measured and compared. For an array of N elements arranged arbitrarily the voltage induced in a probe close to one element is the vector sum of N voltages which depend in magnitude and phase on the positions of the elements and the currents I_i in them. The voltage induced in the probe when it is near the j^{th} element may therefore be written as:

$$V_j = \sum_{i=1}^{N} \alpha_{ij} I_i$$

where α_{ij} is a coefficient of the voltage induced by the i^{th} element in a probe at the j^{th} element, determined only by the physical structure of the array and the position of the probe. The coefficients α_{ij} are evaluated in a separate experiment using only one element of the array and the probe.

Thus if V_j is measured for every element and α_{ij} is known for each element, then the element currents can be obtained from the solution of the resulting N simultaneous complex-number equations. These may be transformed into 2N real-number equations by considering the real and imaginary parts separately (see Appendix, Section 6.3.).

2.2. Instrumentation

If the coefficients α_{ij} are small for $i \neq j$ the ratios of the probe outputs are approximately equal to the ratios of the currents in the radiating elements. In order to reduce errors it is desirable to approach this condition as nearly as possible and this can be done by using a type of probe which discriminates against the currents flowing in adjacent elements. For horizontally-polarized arrays this may be achieved by using a small loop in a horizontal plane as a probe.

The accuracy of the method is then governed in the main by the following two considerations:

(i) Positioning accuracy of the probe in front of every element.

(ii) Measuring accuracy of the output of the probe in every position.

Implicit in these considerations is the need for similar care and accuracy when determining α_{ij} in the calibration, described later in this section. In all the measurements with a probe the relative position of the probe to the nearest element of the array has to be standardized to very close limits so that the voltage induced in the probe is repeatable to within the accuracy of measurement.

With the probe held in a jig which clips on to the element concerned, the separation of the probe from the element can be maintained at about 3 in ± 0·1 in (7·5 cm ± 0·25 cm). Measurement of amplitude and phase can then be repeated without significant variation.

Fig. 1 shows the block schematic of the measuring technique. In order to eliminate errors due to changes in electrical length of cables and to slow drift of the oscillator frequency, two probes are used, one of which is attached to a reference element on the array while the other is used to investigate the other elements in turn. The amplitudes and phases of the voltages induced in the two probes are compared by quickly switching from one probe to the other.

The amplitudes and phases of the voltages induced in the probes are compared with the aid of a G.R. Admittance Meter^4 and a suitable receiver. In this method the voltage from each probe in turn is balanced against a voltage fed directly to the receiver via the admittance meter and an attenuator.

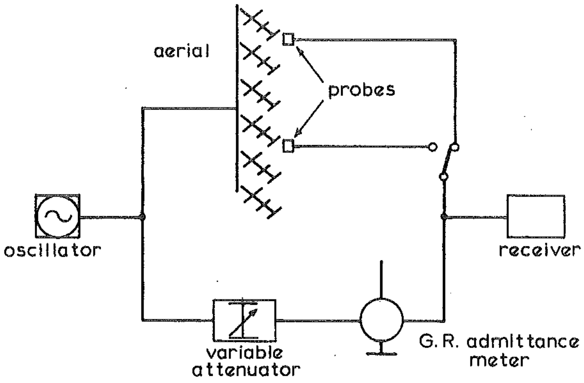

Fig. 1 - Block schematic diagram of method of measurement

The three coupling loops of the admittance meter are adjusted until the receiver indicates a null input signal; the amplitudes of the two voltages being compared are then equal and their phases differ by 180°. The range of control of the meter is 360° of phase and 50 dB of amplitude. The readings are obtained in real and imaginary quantities, both calibrated on a -20 0 +20 scale. With the three loop-controls set to zero the admittance meter introduces slightly greater than 100 dB of attenuation; when set at full-scale the attenuation is approximately 50 dB. When used with an attenuation of 80 dB in order to balance out a low-level signal, the amplitude accuracy is about ± 10% and the phase accuracy about ± 5°. In the region of 50 dB attenuation the meter is most accurate, i.e. about ± 1% in amplitude and ± 1° in phase. The variable attenuator in series with the meter is used only at the start of a series of measurements so as to bring the maximum probe voltage within range of the admittance meter. For maximum accuracy the relative levels of the probe and admittance-meter outputs should be adjusted until the meter is used at almost full scale. Since the relative powers fed into the elements of a multi-tier array are usually approximately equal the meter is then used near to maximum sensitivity for all tiers.

As the two probes and associated cables cannot be made electrically identical their relative outputs if interchanged will differ slightly. In order to eliminate this variation and to obtain a set of N voltages for the array, the probes are interchanged and two sets of N - 1 readings obtained. These are transformed into polar form and the geometric mean of corresponding amplitudes and arithmetic mean of corresponding phases calculated.* This gives a set of N - 1 relative voltages expressed in polar form $A_j\angle\phi_j$ where the subscript j denotes the jth element, the voltage corresponding to the reference element being $1\angle 0$.

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* It can be shown that this method of averaging exactly eliminates differential errors between the two probes. The difference between the phases of the two probes should be less than 90° to avoid a 180° ambiguity in the phase ϕ_j of the voltage V_j. More important, the difference should be as small as possible since similar ambiguities in ϕ_j can also arise when this angle is in the neighbourhood of 0°. Special checks were made to avoid such ambiguities (see Appendix).

The calibration experiment to determine α_{ij} for all the elements of an array is performed with one element of the array and the two probes. One probe is attached to the element and the other is placed in turn at all the physical positions that it would occupy if all the other elements were present. The two probes are then interchanged and the averaging procedure previously described carried out to determine the relative voltages, which this time are the coefficients α_{ij}.

3. EXPERIMENTAL VERIFICATION OF ACCURACY

A preliminary experiment was performed using a simple array of six dipoles, with the probe carried along a straight line parallel to the array by a three-wheeled platform on a track. The loop was positioned opposite each dipole in turn with a separation of about 6 in ± 0·25 in (15 cms ± 0·6 cms) and α_{ij} evaluated for the corresponding separations using a single dipole from the array. The radiation pattern from the array was also measured in the conventional manner on a turntable.

The results obtained were encouraging in that the v.r.p.s produced by computation and by rotation were very similar, disagreement in the main being in the ratios of sidelobes to main lobe magnitude and in the depths of the nulls. Some of the errors were due to inaccurate probe location and some were due to the curvature of the wave front over the length of the aerial in the turntable measurement.

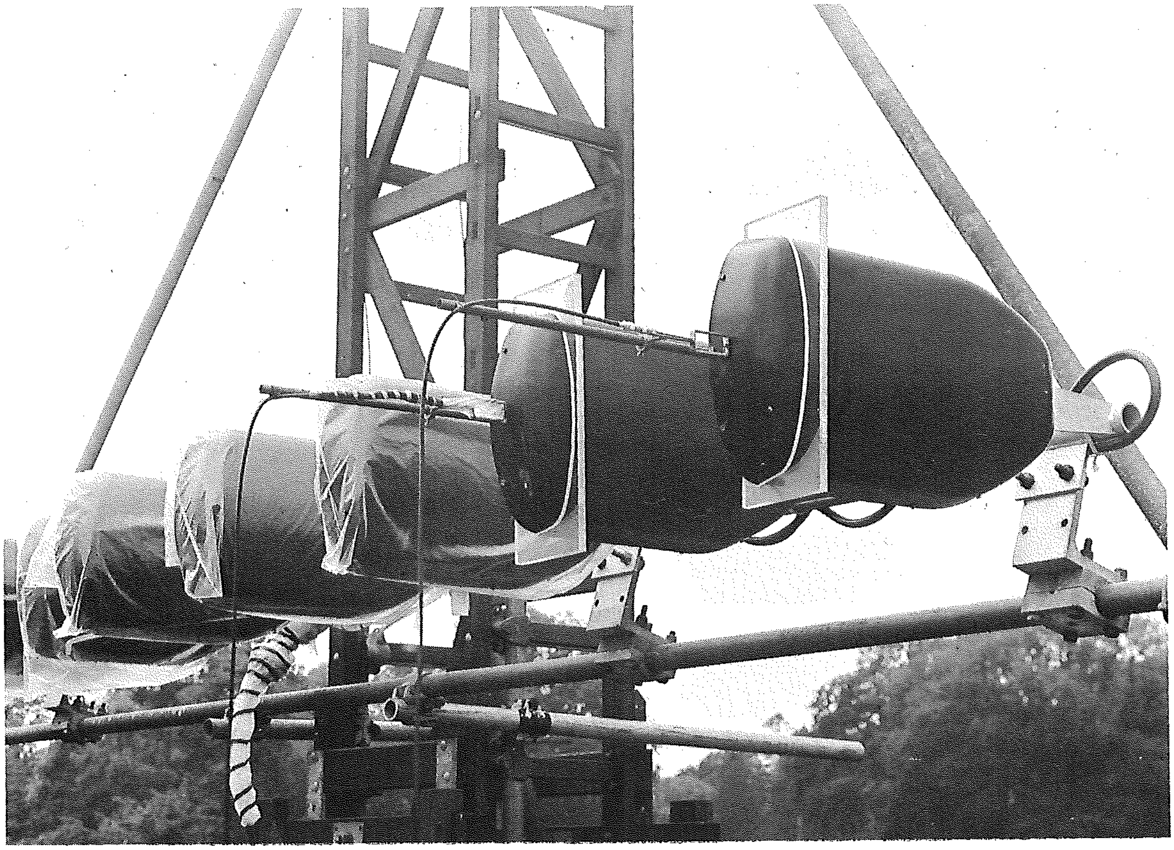

Fig. 2 - Probes attached to part of Crystal Palace Channel 33 aerial

The method was then developed for the measurement of the Channel 33 aerial at Crystal Palace. This aerial consists of columns of radiating elements mounted on the corners of the tower. Each column radiates over a sector of 90° so that the complete aerial virtually consists of four aerials, each of whose v.r.p. must be measured. In the complete aerial each column contains 40 elements. To test the accuracy of the method the v.r.p. of a spare panel of 10 elements (a quarter of one column) was measured by the two methods. As the length of the panel was 15 ft (4·5 m) the receiving aerial had to be positioned some 250 ft (75 m) away from the turntable to minimize the curvature of the wave front, but even so there was a 20° phase difference between centre and ends of the aerial.

Fig. 2 shows the panel mounted horizontally, with measuring loops attached to two of the elements. The latter are not simple dipoles but comprise an end-fire array of three parallel dipoles, separated by $\lambda/4$ and driven with current ratios of approximately 1 : 2 : 1, enclosed in a glass-fibre box. Thus a measuring loop close to the box will sample a field which is due to three dipoles. However, as the three dipoles and their feeders are diecast it was assumed that all the tiers were physically similar and hence that the contribution to the induced voltage from the element to which the loop was attached was proportional to its effective radiating current, the constant of proportionality being the same for all elements. This assumption is not entirely justified, however, since mutual impedance between adjacent elements will tend to upset the 1 : 2 : 1 current relationship.

A jig was made of perspex and tufnol to hold a small rectangular loop close to the front of the glass fibre cover (see Fig. 2); this enabled the loop to be positioned easily and accurately. Allowance was made in the calibration procedure for the fact that the radiating elements were staggered; this design feature of the aerial was intended to improve the uniformity of the horizontal radiation pattern of the complete aerial. With the panel still mounted on the turntable (see Fig. 2), the currents in the ten tiers were measured using the two-loop technique and the v.r.p. computed.

A direct comparison with the v.r.p. measured by rotation did not, in this case, constitute a valid test of the accuracy of the probe method because the latter normally yields the far field v.r.p.; this was not measured by the turntable method because the curvature of the wavefront of the illuminating signal was too great. To enable a valid comparison to be made the v.r.p. which the aerial would have at the finite distance at which the turntable measurements were made was therefore calculated from the measured element currents. Fig. 3 shows a comparison of v.r.p.s at this finite distance measured by the two methods, at two different frequencies. Perfect agreement was not obtained nor was it expected, because of the effect on the current distribution within elements of mutual impedance between them. Nevertheless, the agreement is seen to be reasonable, particularly at the higher frequency.

The method described was subsequently used as part of the acceptance tests of the Crystal Palace u.h.f. aerial at the manufacturers' works. As it was not convenient to erect more than ten tiers of the aerial for test purposes at any one time, the measurements had to be confined to ten-element panels. In the complete aerial, mutual impedance between the end elements of adjacent panels will cause the currents in these elements to differ slightly from the measured values; these changes in current, however, would not be expected to exceed more than 10% so that their effect on the v.r.p. of the complete aerial is relatively small.

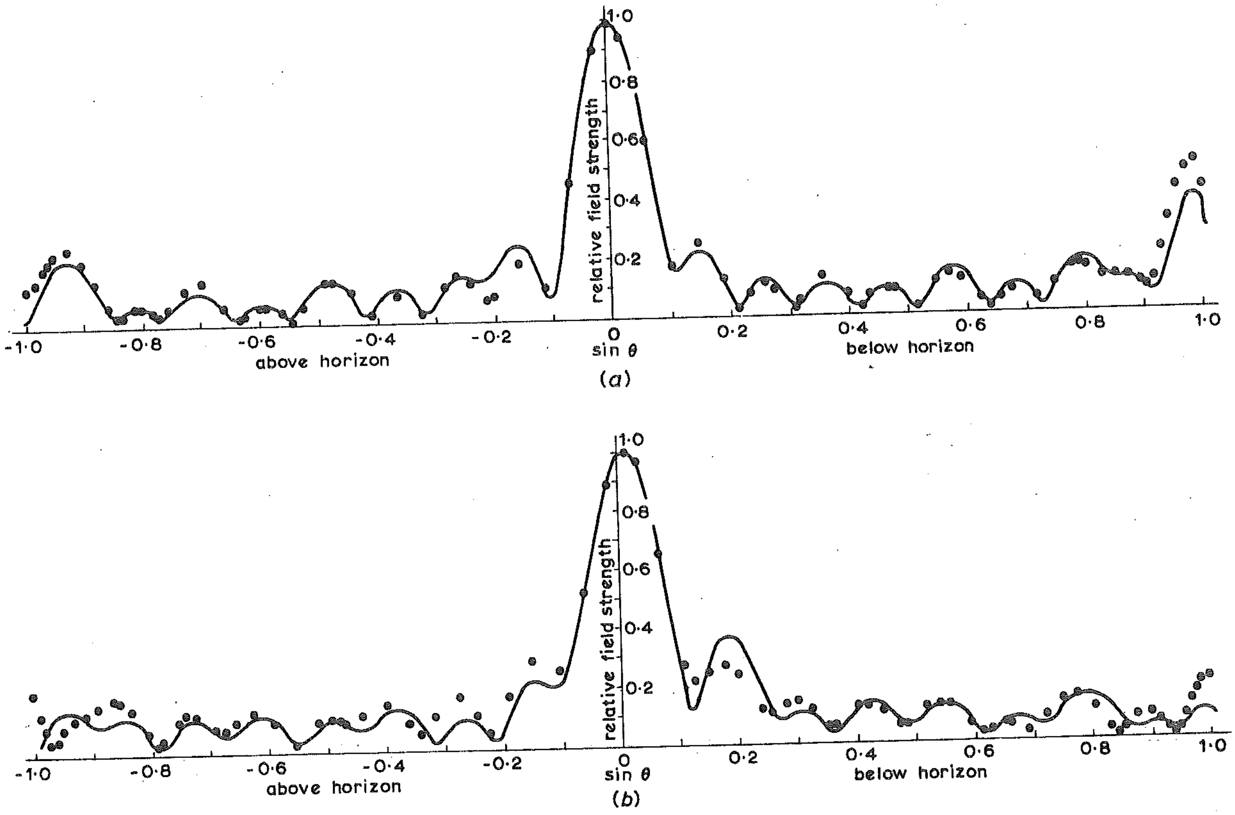

Fig. 3 - Comparison of v.r.p.s of 10 tiers of Crystal Palace Channel 33 aerial

(a) 565 Mc/s
(b) 510 Mc/s

—— computed from probe measurements
● ● ● measured by rotation

The v.r.p.s are plotted as a function of sinθ, where θ is measured from the normal to the array

In computing the v.r.p. of the complete aerial some uncertainty was introduced because the relative amplitudes and phases of the fields radiated by the four individual panels could not be measured. This difficulty was overcome by assuming that the power fed into each panel was the same, the relative phases of the panels being adjusted so that their resultant far fields had the intended phase relationship.

The only satisfactory way of eliminating errors due to changes in the currents in the end elements and due to uncertainty about the relative fields of the four panels would be to repeat the measurements on the complete aerial when finally erected. Other methods of measuring its v.r.p. (such as the use of a helicopter) might, however, be more convenient.

4. CONCLUSIONS

Although the application of this method of v.r.p. measurement has so far been confined to the Crystal Palace Channel 33 aerial, there appears to be no reason why it should not be used for any multi-tiered aerial having similar tiers, provided the coefficients a_{ij} can be evaluated.

The advantage of the method is that it does not require a large measuring area but can be carried out wherever it is convenient to erect the aerial, providing that due care is taken to avoid ground reflexion errors. The measurement procedure is relatively simple but the interpretation of the measurements requires the use of a digital computer since the solution of the large number of simultaneous equations involved would otherwise be virtually impossible. Although the measurements can be carried out on isolated sections of an aerial and the results subsequently combined, greater accuracy is achieved if they are carried out on a complete aerial.

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2. JASIK, H.: Antenna Engineering Handbook, (McGraw-Hill, 1961), Section 2, pp.31-35.

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6. APPENDIX: COMPUTER PROGRAMMES FOR V.R.P. CALCULATIONS

Two computer programmes* have been developed for future v.r.p. determinations which reduce the amount of calculation to be performed by the acceptance-test engineer. One is for the case where the whole aerial is available for measurements, while the other is designed to handle the results from separate panels of an array.

The determination of the v.r.p. in either case can be divided into two parts:

(i) Measurements with probes

(ii) Insertion of results of probe measurements tabulated as in Section 6.1. plus ancillary data listed in Section 6.2. into computer programme.

It is to be noted that in the case of separate panels more data is required for the computer than for the whole-aerial case.

6.1. Organization of Probe Measurements

With one probe on a reference element a set of N - 1 readings are taken with the other probe on each of the other elements in turn, check readings of the reference probe output being taken at each position. The probes are then interchanged and another set of N - 1 readings obtained. The two sets of readings should be tabulated in the following manner:

	REF. (1)		UNKNOWN (1)		REF. (2)		UNKNOWN (2)	
	REAL	IMAG:	REAL	IMAG:	REAL	IMAG:	REAL	IMAG:
1								
2								
3								
.								
.								
N-1								

These probe measurements are used to compute the coefficients of the simultaneous equations. A running check is carried out on the phase term, ϕ_j, by comparing the phase difference of the two probe outputs tier by tier.

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* Due to Mr. R.W. Lee

6.2. Ancillary Data Required for Programme

(i) Whether whole aerial or separate panels

(ii) Position of reference element with respect to whole aerial or position in each panel and position of panel in whole array

(iii) Frequency of measurement

(iv) Some code number to identify with (ii) which corner or face of the mast the panel or array comes from

(v) Total number of tiers

(vi) Range of angles for which computation to be performed

(vii) Physical position of every tier in array specified in two dimensions (inter-tier spacing and stagger) in wavelengths

(viii) The matrix coefficients for solving the simultaneous equations for each physically dissimilar panel or array

(ix) V.R.P. of single tier

(x) Relative amplitude of feeds between panels

(xi) Relative phase of feeds to each panel

} Only required for separate panel case

From this data the computer will plot a normalized v.r.p. for all four quadrants for a given array and will also compute the gain of the array relative to a half-wavelength dipole.

Separate computations must be made for each frequency but v.r.p.s for up to eight columns round the mast can be computed in one operation.

6.3. Determination of Element Currents

V_j is the measured probe voltage, α_{ij} is the coefficient between the i^{th} and j^{th} elements and I_i is the radiating current flowing in the i^{th} element; these three quantities may be expressed as follows:

$$V_j = A_j(\cos\phi_j + j\,\sin\phi_j)$$

$$\alpha_{ij} = \beta_{ij} + j\gamma_{ij}$$

$$I_i = X_i + jY_i$$

The complex number equations are then separated into pairs of real-number equations of the form:

$$A_j \cos\phi_j = \sum_{i=1}^{N} (X_i\beta_{ij} - Y_i\gamma_{ij})$$

$$A_j \sin\phi_j = \sum_{i=1}^{N} (X_i\gamma_{ij} + Y_i\beta_{ij})$$

The quantities X_i and Y_i are then determined by solving these equations on a digital computer. To enable the computer to handle the data they are arranged in the following form:

$$\begin{bmatrix} \vdots \\ A_j\cos\phi_j \\ A_j\sin\phi_j \\ \vdots \end{bmatrix} = \begin{bmatrix} \cdots & \beta_{ij} & -\gamma_{ij} & \cdots \\ \cdots & \gamma_{ij} & \beta_{ij} & \cdots \end{bmatrix} \begin{bmatrix} \vdots \\ X_i \\ Y_i \\ \vdots \end{bmatrix}$$

Thus for an N tier array the first matrix is a 1 x 2N matrix of measured quantities, the second matrix is 2N x 2N and is determined solely by the physical structure of the array, and the third matrix is the 1 x 2N matrix containing the unknown element currents.

These 2N simultaneous equations can be easily solved by means of an electronic digital computer, and being well-conditioned (constant leading diagonal = β_{11}) there is usually no problem with size. For example, using the Elliott 803 M1 programme with the 4096-bit store the limitation is that $(n+2)^2$ should be less than 11,160, where n is the number of simultaneous equations; i.e., up to a 50-tier array can be dealt with in this manner.

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